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Ice-dams, outburst floods, and movement heterogeneity of glaciers, Karakoram

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ABSTRACT

The paper concerns ice dams and glacial lake outburst floods (GLOFs) in the Karakoram. Some 146 events are identified, including 30 major disasters. Large downstream populations and major infrastructure are threatened. Risk factors differ from recent reports of other Himalayan GLOFs associated with glacier recession and global warming. Ice dams are largely or entirely active ice, put in place by advancing glaciers. Climate change is a factor, but the ice cover in the Karakoram has sustained, and even some increase in mass. Surge-type glaciers comprise or affect~70% of our inventory. The most frequent, large GLOFs come from local clusters of glaciers in five sub-basins, given special attention here. In four there were new ice dams formed since 2008 and two generated dangerous GLOFs. An urgent need arises to track short-term ice and lake behavior and how surge dynamics may be involved. Satellite images and DEMs are employed in cross-correlation feature tracking and elevation change respectively. The glaciers of interest all exhibit irregular movement, including recent advances, but with great variability and no clear relation to climatic fluctuations.

Keywords: glacial lake outburst floods (GLOFs), Karakoram, remote sensing, DEMs, Surface velocity.

1. Introduction

In the upper Indus and Yarkand basins of the Karakoram, historical records of more than 146 glacier lake outburst floods (GLOFs) can be traced to ice-dammed lakes (Hewitt, 1982; Hewitt & Liu, 2010; Iturrizaga, 2005c; Zhang, 1992) (Table S1 and S2). Others have been reported in neighbouring ranges including Nanga Parbat, the Hindu Raj, and Pamir Wakhan (Ashraf et al., 2017; Gruber & Mergili, 2013). The most destructive of these GLOFs brought at least 19 major disasters on the Indus, and 11 on the Yarkand (Hewitt,

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2014). Some of the flood waves travelled and brought damage as much as 500 km downstream on the Yarkand, and 1,200 km on the Indus. The continued occurrence of such GLOFs in the former, and indications of a 21st century resurgence of the ice dam risk for the latter, are of concern for large populations and expanding infrastructure downstream (Carrivick & Tweed, 2016).

In the impoundments of interest, glacier ice is the main or only barrier, put in place by glacier thickening or advance (Tweed, 2011). Nearly all the larger Karakoram GLOFs originate from the advance of the terminal lobe into a main, ice-free river valley of which the glacier is a tributary (Fig. 1). These are what Ashley (1995) calls "ice-dammed, river-lakes". In some cases, a thickening main glacier may impound a lake in an ice-free tributary, one of which, the Khurdopin in Shimshal, is known to generate major GLOFs (see below).

Ice dams form rapidly, rarely last more than one ablation season and when a failure occurs in all but a very few cases. Some lakes fill quickly and only survive a few weeks before draining. They may, however, be resealed several times in a given episode, if the glacier continues to advance. This is a feature of some of the most dangerous glaciers [e.g. Chong Kumdan (ID 27) 1926-33; Kyagar Glacier (ID 26) 2014-2016]. The lakes are 'self-dumping' (Clarke, 1986), in that drainage depends on interactions of ice barrier and lake, their dimensions, geometry and dynamic instabilities described below.

Equally, if not more significant, glacier dynamics and mass balance in the Karakoram are complicated by the many surge-type glaciers, possibly absent from the rest of the Himalaya. A large fraction of Karakoram glaciers with histories of ice dams compiled below, are surge-type (Table 1). Their behavior tends to buffer or reconfigure relations to climate (Bhambri et al., 2017). Surge-type glaciers are found in the Pamirs, also associated with some ice dams and anomalous relations to climate change (Lin et al., 2017).

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Ice dam incidence in the Karakoram is further complicated by impacts of large rock slope failures that descend onto the glaciers (Gardner & Hewitt, 1990; Hewitt, 2009). Landslide debris can partly or fully protect large areas of ice against ablation, leading to glacier thickening and advances that may be out of phase with climatic events. A recent example, bringing a serious ice dam threat, is Chillinji Glacier (ID 5) in Karambar valley, described below (Deline et al., 2014) (Fig. 1). There are remnants of dozens of prehistoric landslides that travelled onto or over glaciers, sufficient to indicate a recurring influence on glacier fluctuations through the Holocene (Hewitt, 2013).

Figure 1 around here

In a pioneering 1905 survey of "glacial reservoirs and their outbursts" Rabot (1905) represented ice dams as globally the most significant, and the only cases he reported for the Karakoram. His evidence was derived entirely from within the Little Ice Age (LIA), suggesting ice damming reflected the global cooling and glacier advances of that period, reinforcing the case for climate-driven change. Most reports in our inventory of large Karakoram GLOFs from ice dams are for the 19th and early 20th centuries. This is so even though, to the 1960s, reports were patchy in time and space, a majority of events located in uninhabited and temporarily visited areas. Many only became known from devastation far downstream, and visits after the dams were breached (Mason, 1930, 1935). Some early explorers (Gunn, Todd, & Mason, 1930; Ludlow, 1929; Strachey, 1853; Visser, 1932) gave rough estimates of ice dam dimensions. Data on dam formation, height, and lake volumes were poorly constrained. In general, for the Karakoram, there is a critical lack of the kinds of glaciological information that might explain, let alone help predict, these complexities.

A recent noteworthy study documented 98 GLOFs in the Karakoram (Emmer, 2018). Our study updates and documents 146 GLOFs events. It includes investigations of ice-dammed lakes, outburst floods, and movement heterogeneity focused on 31 Karakoram

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glaciers, combining remote sensing and archival datasets. Mason (1935) referred to most of the same cases as "threatening glaciers" and the greatest number on record were in the LIA, continuing to the late 1920s in the Karakoram (Kick, 1989). From the 1930s, there was a marked reduction of the glacier cover in the Indus to the late 20th century, possibly as much as 5%, responsible for much-reduced ice dam activity (Hewitt, 2014)

Karakoram ice-dams raise different issues from GLOF risk reported recently in other parts of the Himalaya (Bajracharya and Mool., 2009; Harrison et al., 2018; Ives et al., 2010; Kattelmann, 2003; Richardson and Reynolds, 2000). Most of the latter involve glacial lakes forming at the margins or termini of receding glaciers. A comprehensive inventory for the Hindu Kush-Karakoram-Himalaya (HKH), recently updated, shows these other types of dam are the most numerous and widespread in the region (Maharjan et al., 2018). The great majority are, however, small, or less than 0.05 km^2. Melt water is ponded in pre-existing or newly formed depressions beside or below waning glaciers, or in basins behind terminal moraines or in bedrock basins following glacier recession. A type of 'ice-dammed lake' (I) is recognized but comprises barely one percent of HKH glacial lakes recognized. None reaches dimensions of the large ice-dams identified here. These other classes of glacial lake are described by Iturrizaga (2011) and Tweed (2011). In Bhutan, Nepal and the Indian Himalaya, a few cases have given rise to the most destructive of recent GLOFs, and are generally attributed to global warming (Carrivick and Tweed, 2016; Haeberli et al., 2016; Harrison et al., 2018; Maharjan et al. 2018).

In the Karakoram too, these other types of glacial lakes are more numerous than ice-dams. They generate the most frequent and widespread GLOFs reported in recent decades (Ashraf et al., 2017). Many are also associated with glacier retreat and stagnation, if mostly in lesser ranges rather than the main Muztagh Karakoram. However, to date they have been

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relatively small and local threats within the mountains. They differ from the ice-dammed lakes in incidence, potential to generate large GLOFs, and stability.

Whereas most of the lakes in the HKH inventories have persisted for years or decades without giving rise to GLOFs, the Karakoram ice dams identified here form and drain quickly. Readily missed by mapping surveys, they require dedicated movement and terminal advance monitoring to pick up short term fluctuations, as applied recently to Kyagar Glacier (Haemmig et al., 2014; Round et al., 2017). Risk assessment is frustrated by the greater numbers of episodes of advance and cross-valley ice barriers that have failed to seal a dam, and by ice-dammed lakes that drained slowly without a destructive GLOF. Nevertheless, the dozen or so largest ice-dammed lakes are singled out by catastrophic outbursts.

Ice dams and GLOFs monitoring has been improved in recent decades thanks mainly to remote sensing (Haemmig et al., 2014; Hewitt & Liu, 2010; Mayer et al., 2008; Round et al., 2017). Since GLOF risk for ice-dammed lakes is controlled mainly by ice dynamics, geometry and dam stability, recent developments using automated feature tracking for glacier movement are promising. Experiments with the technique have shown highly variable rates of movement along most Karakoram glaciers, from year to year and between individual glaciers. They are indicative of great movement 'heterogeneity' (Bhambri et al., 2017; Copland et al., 2009; Paul et al., 2017; Quincey et al., 2011; Quincey & Luckman, 2014; Rankl et al., 2014). The findings also reinforce older reports of Karakoram glaciers having a notorious lack of consistency of advances and retreats. Mason (1930), who made the first major compilation, observed that

> …Ultimately, the movements are due to climate and snowfall, but the factors are so varied that the snout movements appear to be peculiar to each glacier. There

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> may be little resemblance between… neighbouring glaciers… even if they have the same exposure; sometimes there is no similarity between… two branches of the same compound glacier; occasionally one side of a glacier tongue may be advancing while the other retreats…. (Mason, 1930), (pp. 218–219).

His observations were based largely on the final decades of the LIA, but agree with our findings in a time of global climate warming. Variable and generally irregular and independent glacier fluctuations appear to be a prevailing characteristic of these glaciers and with poor, complex or absent correlations with climate trends.

Our study presents data to update and confirm the incidence of ice dams in the past two centuries. It uses cross-correlation feature-tracking experiments and DEM difference maps to reveal the contemporary dynamics of the glaciers involved. Automated feature tracking seems particularly promising. Past experiments have shown highly variable rates of movement along most of the glaciers involved, locally and from year to year. However, availability of cloud-free Landsat satellite images is a huge challenge to accurately monitor, say, active surges at regular intervals (Quincey & Luckman, 2014). The present study reports new analyses of ~25 years (~1990-2017) of inter-annual variability of the surge and non-surge glaciers known to have created ice dams, based on Landsat, ASTER, Sentinel and Planet high-resolution images (3m cell size).

Build-up, stability, and breaching of ice-dammed lakes depend on interactions between ice dynamics, size and rate of infilling of the reservoir, including the ratio of water depth to ice thickness, mass and stability of terminal lobes (Glen, 1954; Grinsted et al., 2017; Kjeldsen et al., 2017; Knight & Tweed, 1991; Nye, 1976). Several studies link GLOF occurrence to the acceleration of the glacier concerned (Grinsted et al., 2017; Kjeldsen et al., 2017). Periodic drainage of ice-dammed lakes can follow variations in glacier velocity

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(Knight & Tweed, 1991), or ice dam response after drainage (Mayer et al., 2008). Thus, it is of some importance to know whether tracking glacier dynamics up-valley of potential dam sites might help identify constraints on dam closure, stability, lake dimensions, and dam collapse.

The main objectives of the paper are:

(1) an updated inventory of ice dams and related GLOFs combining historical sources and remote sensing data;

(2) risk factors relating to a conspicuous local clustering of Karakoram ice dam sites within the region;

(3) recent evidence of surface displacement and elevation changes of surge-type and non-surge type glaciers involved in ice dam generation; and

(4) discussion of the relations of movement and ice dam formation, and preliminary implications for monitoring glacier behavior, lake formation and dimensions, an which glaciers to observe and set up GLOF warning systems.

Table 1 around here

2. Materials and methods

2.1. Historical inventory

Adequate inventories of GLOFs and evidence of their generation depend upon historical sources to provide adequate time series and perspective (Emmer, 2018). The incidence and chronologies of ice dams and GLOFs is updated here (Table S2; Fig. S1) based on ground observations from one author's previous extensive field work (Gardner & Hewitt, 1990; Hewitt, 2005, 2007, 2013, 2014) and many published and archival records (Grant and Mason, 1940; Hayden, 1907; Hedin, 1917; Hewitt 1982; Kick, 1989; Longstaff,

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1950; Mason, 1928, 1930, 1935; Strachey, 1853; Visser, 1926; Visser and Visser-Hooft, 1938). Published maps and ground photographs were also used to document and assess past ice dams, GLOF events and compared with the present survey (Hewitt, 2014).With these background findings, we turn to the use of remote sensing for recent evidence glacier movement profiles and related features.

2.2 Satellite images and DEMs

Multi-year and continuous observations are required to track annual and inter-annual variations of glacier surface displacement. The longest available satellite program series, Landsat MSS, TM, ETM+, and OLI, were used for the present study; including ~400 Landsat scenes from 1989 to 2017 (Table S3). The Landsat 7 ETM+ scenes are affected by scan line errors since 2003 except in the middle portion of scenes (~22 km wide) due to the permanent failure of the scan line corrector (SLC). Therefore, ASTER data were used (~200 scenes) from 2000 to 2015 and Sentinel data (~20 scenes) since 2015 to complete coverage at an annual scale (Table S3, S5). In addition, four Planet high-resolution images were acquired to understand the change in ice dam of Kyagar Glacier (Fig. 2). Satellite images during August to November, with limited cloud cover, were used mainly to automate feature tracking. The Landsat and Sentinel satellite scenes were acquired from USGS (United States Geological Survey; http://earthexplorer.usgs.gov/).

Figure 2 around here

We also used 32 ASTER stereo scenes for DEM generation (Kääb et al., 2002; Kargel et al., 2005). The ASTER product (AST_L1A) was obtained from the NASA EARTH SCIENCE DATA website (https://search.earthdata.nasa.gov/) under the flagship of the Global Land Ice Measurement from Space program (Kargel et al., 2005). AST_L1A

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products contain 14 VIS, NIR, SWIR and thermal-infrared (TIR) spectral bands at 60 km-wide ground coverage. The stereo image data lies in the NIR wavelength region from 0.78 to 0.86 μm and includes nadir- and aft-looking scenes (3N and 3B). In addition, three Cartosat stereo scenes were also acquired from the National Remote Sensing Centre (NRSC) for DEM generation. Glacier outlines were acquired from the Bhambri et al. (2017) and RGI Consortium (2017) and modified where required using 2016-2017 Landsat OLI images (Gardelle et al., 2013).

The Shuttle Radar Topography Mission (SRTM1) DEMs were also acquired from the USGS (United States Geological Survey; http://earthexplorer.usgs.gov/). The SRTM obtained elevation data of Earth surface between 56° S and 60° N during February 11-22, 2000. The ~10m absolute vertical accuracy has been reported for SRTM DEM (Farr et al., 2007). Several glaciological studies have used SRTM data as a reference DEM to compute elevation difference maps and mass budget estimation for the surge (Bolch et al., 2017; Pitte et al., 2016; Round et al., 2017) and non-surge glaciers (Berthier et al., 2016; Bolch et al., 2017).

2.3. Surface displacements

For automatic surface feature tracking a normalized cross-correlation (NCC) algorithm was used. We computed surface flow velocities from two successive pairs of Landsat, Sentinel or ASTER images using CIAS Image correlation software (Heid & Kääb, 2012a; Kääb & Vollmer, 2000). Various studies have successfully used this for computing multi-temporal glacier surface velocity in the Karakoram (Bhambri et al., 2017; Heid & Kääb, 2012b). We also used 64 surface displacement data sets generated in a previous study (Bhambri et al., 2017) for six glaciers with others computed (203) in the present study, to identify spatio-temporal variations at an annual scale for 18 glaciers (Table 1; Table S4).

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The planimetric shift found in all Landsat and Sentinel images at individual glacier scales, was visually checked and co-registered where required, using the projective transformation algorithm of the ERDAS Imagine Photogrammetry suite (Bhambri et al., 2017). Multiple satellite images were employed covering both active and quiescent phase surface flow velocities for surge-type glaciers. The search window size ranged from 30 × 30 to 250 × 250, and a reference windows size of 10 × 10. CIAS provides surface displacement in 'txt' format, which we converted in vector data using ArcGIS. Filtering and cleaning have been recommended to omit spurious surface displacements (Heid & Kääb, 2012b; Kääb & Vollmer, 2000). As suggested by Redpath et al. (2013), we excluded ≤0.6 correlation coefficient from the glacier flow data set. Directional filtering was also used to eliminate spurious displacements (Heid & Kääb, 2012b; Kääb & Vollmer, 2000). Finally, velocity vectors were visually evaluated against their corresponding satellite images. Any remaining false displacements were removed. All the accepted surface displacements were then converted to an annual and daily scale (Paul et al., 2017; Quincey et al., 2011, 2015). The temporal surface displacements (color ramp) were generated from the central line (Fig. 3 and 4; Fig. S2, S3) of the studied glaciers.

2.4. DEMs generation and processing

A total of 32 ASTER and 03 Cartosat 1 DEMs were generated using the orbital ancillary data by ERDAS Imagine Photogrammetry Suite 2015. Since it is a huge challenge to collect ground control points (GCP) in rugged mountain areas, we did not use any GCP for the generation of the ASTER and Cartosat 1 DEM. A well-known DEM product of ASTER (AST14DMO) and Cartosat 1 DEMs are used by many studies (Agarwal et al., 2017; Berthier et al., 2016; Bolch et al., 2017) for glacier mass balance estimation are also generated using the orbital ancillary data without any GCP.

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A total of ~100 tie points (TPs) were used to improve the sensor models for all the ASTER and Cartosat 1 DEMs. The ASTER DEMs are usually inadequate to identify changes in topographic details of high slope mountain terrain (Kääb et al., 2002). However, the main purpose is to track the change in the ice dam conditions (thinning and thickening) by the elevation difference maps, using multiple DEMs. Several previous studies have used ASTER DEMs to study the geometric evolution of surge-type glaciers (Pitte et al., 2016). The overall quality of the generated raw DEMs near the glaciers appeared promising. Surface area and moraines were generally completely covered, but the DEM sometimes failed because of poor contrast in snow-covered areas, or to cloud cover and cast shadows. These were excluded manually using shaded relief from the resulting DEM (Agarwal et al., 2017).

2.5 Co-registration of DEMs, outliers removal and elevation changes

A proper co-registration of multiple DEMs is required to ensure corresponding pixels in the two DEMs being compared represent the same ground position. Many studies have reported systematic biases in elevation difference maps due to horizontal shift (Berthier et al., 2016; Gardelle et al., 2013; Nuth & Kääb, 2011). To address this we co-registered the 32 ASTER and 03 Cartosat 1 DEMs to reference SRTM DEM using the following universal co-registration approach developed by Nuth and Kääb (2011):

$$dh = a\,.\,\cos(b-\psi)\tan(\alpha) + \overline{\mathrm{dh}} \qquad (1)$$

where dh, a , b represents the individual elevation difference, the magnitude of the horizontal shift and the direction of the shift in vector respectively. The α, ψ and $\overline{\mathrm{dh}}$ terms present slope, aspect and overall elevation bias between the two DEMs respectively. The equation utilizes pixels of off-glacier slope, aspect and elevation differences. Since minimal horizontal shift (<1 m) could not be achieved in the first iteration, a maximum of five

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iterations were carried out to adjust the all the ASTER and Cartosat DEMs with reference SRTM DEM (Agarwal et al., 2017). All the ASTER DEMs were co-registered with the reference SRTM DEM on stable terrain with slopes < 45◦ (Berthier et al., 2016) as these DEMs usually failed at higher slope (Kääb et al., 2002).

Our study computed relative surface elevation change, instead of absolute, because of the lack of GCPs for DEM generation. We subtracted all the horizontally corrected ASTER and Cartosat DEMs from the reference SRTM DEM to compute elevation changes. The outlier elevation ranges above the +150 and -150 were excluded, following a proposal by some studies for the Karakoram glaciers (Bolch et al., 2017). We used average penetration correction of 3.4 m for SRTM DEM C band as proposed by previous study (Gardelle et al., 2013) for Karakoram glaciers. The elevation differences were averaged for each 100-m elevation range that considered as the mean elevation change for the elevation range (Agarwal et al., 2017). The mean surface elevation change was converted into volume change by multiplying the area of the respected glacier altitude range. We distinguished the reservoir and receiving zones based on negative (mass loss) and positive (mass gain) elevation difference and the boundary between both which had 0 m elevation change (Pitte et al. 2016).

2.6 Uncertainty assessment

Several satellite images were used at different spatial and temporal resolutions, which require an uncertainty assessment to bracket the accuracy and significance of the results. The following equation, suggested by Quincey et al.(2015) was used to estimate uncertainty in glacier displacements

$$\sigma = 365 \frac{(C_{pix} + C_{match})\,\Delta x}{\Delta t} \qquad (2)$$

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where C_{pix} is the uncertainty in co-registration in pixels (p), C_{match} is the uncertainty in the matching algorithm in pixels (p), Δx is the image resolution in meters, and Δt is the time interval between the image pair in days. We used 0.5 p values for C_{pix} and C_{match} as proposed by Quincey et al.(2015) (Table S4).

Since there is no sole statistical method for assessment of the uncertainty of surface elevation change measurements we computed three standard statistical estimators such as mean, standard deviation, and normalized median absolute deviation (NMAD) over stable terrain (off-glacier) (Berthier et al., 2016; Vijay & Braun, 2018) (Table S5). Finally, NMAD was used for the uncertainty of surface elevation change.

3. Results

3.1. Ice dams and GLOFs inventory

We documented 146 GLOF events associated with ice dams (Table S1 and S2). Few have received detailed field investigation (Table S2). Most large, destructive GLOFs are associated with intermediate (15-40 km) or large (>40 km) glaciers (Table S1). Some have been as small as 5-6 km in length, while the 68 km Biafo is the largest with a reported GLOF (Table S1). Some surge-type glaciers appear small but can advance 3 to 5 km in a few months and emplace substantial cross-valley lobes (Hewitt, 2014).

With the inventories established, we can begin to identify and compare typical features and dimensions of the glaciers that have formed dams.

3.2. Characteristics of glaciers that form Ice-dams

The glaciers have exceptional elevation spans with the largest, Muchuhar – Hasanabad, having a 5760 m descent from Batura IV peak to the Hunza River -- 25 km in a direct line. Termini can reach much lower than the rest of the HKH. The lowest present-day terminus, a surge-type glacier with an ice-dam history, is Bualtar (ID 30) at 2,250 m asl and

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a total 5100 m elevation range. Surge-type glaciers tend to be steepest. Gradients of Khurdopin (ID 20), Staghar (ID 24), Singhi (ID 25), Kyagar (ID 26), North Chong Kumdan (ID 27) and Kichik Kumdan (ID 28) range between 100 and 150 m/per km (Table S1; Fig. 1). In addition, glacier basins where the larger ice dams originate have watersheds above 6,500 m elevation, in many cases above 7,500 m. The great elevation spans create a complex range of vertically stacked environments through which glaciers travel and to which they must adjust (Hewitt, 2011).

Figure 3 around here

Two ways of classifying Karakoram glaciers are of interest in relation to ice dams; according to dynamics, and to nourishment. There are *surge-type* and non-surge glaciers, and some with characteristics that appear *surge-like* (Bhambri et al., 2017). Terminus fluctuations of such glaciers are indicative of surge cycles rather than direct climate response. The surge cycle involves a Quiescent Phase, possibly decades to centuries long, during which there is a progressive build up of mass in an upper or 'Reservoir Zone'. The lower "Receiving Zone" tends to retreat, thin and stagnate. Eventually, an active surge is triggered that transfers large volumes of ice from the Reservoir into the Receiving Zone, typically in a few months, sometimes over several years. The timing, dimensions, and scope of the surge are peculiar to each glacier. A majority of glaciers with records of ice dams and GLOFs are surge-type. They comprise 70% of our updated inventory (Table S1). Surge intervals and the strength of active surges appear decisive for the timing and severity of the ice dam hazard. Other glaciers creating ice dams are nearly all affected to some extent by surge-type tributaries (Hewitt 2007; Bhambri et al., 2017).

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Karakoram glaciers also involve glacier classes according to nourishment of which four basic types are recognized (Hewitt 2014). The *Turkestan-type* refers to glaciers that are almost wholly avalanche-fed (Hasanabad). The so called *Mustagh-type* is at least 50% avalanche-fed (Khurdopin), and also identified as "incised reservoir" type (Goudie et al, 1984). Glaciers with >50 % direct snowfall are regarded as 'normal', accumulation fed or *Alpine-type (*Biafo*)*. A fourth type is predominantly wind-fed, as snow is redistributed across and between basins during and after snowstorms. This affects most Himalayan glaciers but there are no measurements to confirm the extent. Large, primarily wind-fed glaciers are found in parts of Inner Asia, but those in the Karakoram are small and not associated with significant ice dams or GLOFs.

The great majority of surge-type glaciers forming ice dams are Mustagh or Turkestan type (Hewitt & Liu, 2010). While avalanche nourishment is important throughout the high Himalaya, surge-type glaciers are generally absent outside the Karakoram and Pamirs (Jiskoot, 2011).

Another important factor in relation to glacier behavior and climate change, is the great elevation range over which dam sites are spread (Table S1). The glacier termini involved are at elevations scattered over more than 3000 m vertically (Fig. S1). The lowest site with a major GLOF potential is at Bualtar at 2,250 m asl, the highest Kyagar at 4,753 m. In the far east of the Karakoram, the highest dams are around 5,250 m. The range of elevations means glacier behavior and responses to climate change are influenced by huge gradients and differences of temperatures, precipitation, season lengths, and other atmospheric factors (Hewitt, 2014). Risk assessment and predictions relating to climate change must consider this, rather than just temperature averages, or terminus retreats and thinning at the lowest elevations.

3.3. Glacier movement heterogeneity and related characteristics

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Estimates are provided of surface velocity for 17 surge and non-surge types from 1990 to 2015 or 2017. They extend temporal coverage and diversity of patterns of ice motion found in previous reports (Bhambri et al., 2017; Heid and Kääb, 2012b; Mayer et al., 2011; Neckel et al., 2017; Paul et al., 2017; Quincey et al., 2011,2015; Quincey and Luckman, 2014; Round et al., 2017). Our data confirm the heterogeneity of surface displacement patterns in most glaciers involved (Fig. 3, 4 and Fig. S2, S3). However, no single pattern is revealed that prefigures glacier advances. For all cases there were conspicuously higher velocities in at least one out of the twenty or so years observed; for example, N. Gasherbrum in 2005-7, Urdok in 1996-7, and Staghar, 1989 (Fig. 3). Some exhibit pronounced multi-year higher velocities in the upper part, or 5 to 15 km up-glacier of the terminus (e.g. Yazghil). Preceding and succeeding groups of years had what appear like slow or 'normal' movement profiles for the region. In many cases, similar profiles continued for decades. What these longer-term results (25-26 years) confirm is that ablation zones of surge-type glaciers also exhibit surface displacement instabilities and shifts during the quiescent phase. There are even some temporary 2-, to 3-fold increases in surface velocity (Fig. 3 and 4, Fig. S3). The months-, to year-long accelerations, suggest instabilities of surge-type, but some are associated with steeper tributaries or the base of icefalls, and no clear correlation with surging or ice dam incidence was determined.

Figure 4 around here

The profiles reinforce the evidence of diversity and independence of individual glaciers, already shown to be typical in surge-types (Bhambri et al., 2017). A few glaciers have episodes that resemble the classic single active surge with rapid terminus advance (e.g. Kyagar, and Urdok). In the recent past, some accelerated by one to two orders of magnitude,

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including Staghar, Khurdopin and, after a major tributary surge, Hispar (Bhambri et al., 2017; Paul et al., 2017; Quincey & Luckman, 2014; Steiner et al., 2018). Most newly reported cases and years of accelerated flow were less dramatic. They were of limited extent or involved irregular pulses of movement confined to localized sections of the glacier concerned.

Most ice dams identified appear to form when the active surge phase reaches the terminus; hence in the final weeks or months of surging. However, ice-dams and GLOFs from surge-type glaciers like Khurdopin (ID 20), Kyagar (ID 26), and Chong Kumdan (ID 27) have also occurred many years after an active surge stopped or sharply decelerated. Khurdopin surged in 1998-1999 but small GLOFs recurred in 2000 and 2002. In the final stages of an active surge or after it has subsided, the glacier can still advance sufficiently to reseal a breached dam, even several times, as with Chong Kumdan in the late 1920s and early 1930s (Table S2).

The sealing of a series of dams in a single episode is a continuing possibility at Chillinji (ID 5), Khurdopin (ID 20) and Kyagar (ID 26) (Fig. 1). In other cases or times, emplacement of a cross-valley barrier occurs, but no dam is sealed. The three Kumdan glacier advances in the 21st century are examples. Moreover, during or after recent surges many glaciers did not reach the rivers they have blocked in the past [e.g. Momil (ID 16), North Gasherbrum (ID 22), Staghar (ID 24), Hasanabad (ID 15), Chong Kumdan (ID 27) and Kichik Kumdan (ID 28)] (Fig. 1 and 5; Fig. S4).

Mayer et al. (2011) reported an active surge of the North Gasherbrum during 2003-2007. Our work suggests it had a maximum surge peak in 2006-2007 but there were also sudden accelerations in 1991-1992, 1995-1996, 2008-2009 and 2010-2011 (Fig. 3). Kichik Kumdan Glacier surged 4 times during the 20th century, in 1902-1903; 1935-1936; 1970-1972 and 1998-2000 (Bhambri et al., 2017). Three recurrence intervals cluster between 34

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and 32 years, but the most recent was 26 years. Staghar surged twice, once in 1989-1991 and in 2009-2011. However, the earlier displacement was 3 times higher than the later event. A similar decline in the speed of repeat surges has been reported for Khurdopin Glacier (Quincey & Luckman, 2014).

Non-surge glaciers such as Biafo and Malangutti may not show abrupt changes in surface displacement. They do have marked inter-annual increases or decreases up to 2-, and even 3-fold (Fig. 3). Scherler and Strecker (2012) reported 50% velocity variations at places on Biafo Glacier between 2000 and 2009.

The main overall outcomes underscore the irregularities and lack of consistency in any one glacier or between glaciers. As such, it casts doubt on how far such data can help with prediction of ice dams in the longer term, let alone GLOFs. Yet, even a negative outcome improves what was formerly known about the complexities of glacier behavior in the Karakoram. It suggests an urgent need to identify which glaciers are of concern, and have frequent, if not continuous monitoring of their activity. Although prediction will remain imprecise, because most dam and GLOF episodes tend to occur during or soon after active surges makes the case for using similar monitoring techniques for anticipating hazards.

An important qualification is how Cross-Correlation Feature Tracking (CCFT) fails to pick up short-lived high surface displacement. CCFT missed the highest velocities (>10 m per day) observed on the ground during the Khurdopin 1999 surge, the 1987 Bualtar surge, and the tributary surges of Maedan-, and Shingchukpi-Panmah, among others (Hewitt, 2007). This problem is magnified by gaps in imagery that arise due to cloud, haze, seasonal snow cover or sensor malfunction. It is likely CCFT data is biased towards conditions in pre-, post-, and non-surge or quiescent phases. Availability of daily high-resolution optical images is improving, for instance using Plant Team images (Fig.2). Other

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initiatives include Landsat OLI, Sentinel MSI, ASTER and multiple DEMs programs such as TanDEM-X, Sentinel 1A, 1B Pléiades stereo data. These can further aid understanding of ice dam formation, and the monitoring of behavior and sequences of GLOF events (Round et al., 2017; Steiner et al., 2018). For the moment our data help narrow the search fields across this vast mountain range, by identifying the most promising glaciers, sites and scenarios where higher frequency and resolution monitoring could be used. For this, we now turn to more detailed assessments of individual glaciers, notably certain localized clusters of sites that have dominated the known history of Karakoram ice dams and GLOFs.

Figure 5 around here

3.4. Local clusters of Ice-dam sites

An important and challenging discovery is that a majority of known Karakoram ice dams have been concentrated in a small number of high valleys. A large share of the inventoried dams and GLOFs arise from clusters of glacier termini along five short river sections. One is on the Yarkand, four in sub-basins of the Indus (Fig. 6). All the glaciers are within or along the main axis of the Muztagh Karakoram. On the Yarkand, five glaciers immediately east and north of K2 massif (8,611m), have blocked and impounded lakes on the Shaksgam River. Floods associated with local clusters of Karakoram ice dams from west to east are (1) Karambar-Ishkoman, (2) Hunza Central, (3) Shimshal, (4) Shaksgam, and (5) Kumdan-Shyok clusters (Fig. 6). The sets of ice dam sites occur along 20-30 km stretches of the rivers concerned. A tiny fraction of the entire length of Karakoram river valleys and glacierized area are involved, but the behavior of the termini of 29 of 31 of these glaciers forms a critical part of our main GLOFs inventory (Table 1)

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The glaciers share high altitude sources, great elevation range, and preferential orientation. All descend steeply from upper, frigid basins where precipitous rock walls prevail (Hewitt, 2014). Steep icefall sections are common in the upper parts, but where dams form are relatively gentle ice tongues or lobes.

Orientation involves, almost exclusively, north-to-northwest facing basins and principal flow directions. Some 75% of the glaciers have northerly orientations. Steep northerly aspects shade snow and ice, and may buffer them against climate warming. However, nearly all are lee slope ice masses with respect to prevailing westerly (winter) and southerly (summer) winds. The glaciers are dependent on snowfall mainly above 4800 m (Hewitt, 2014). Downwind slopes of interfluves are associated with higher snowfall. Snow feeding the glaciers is massively redistributed by wind and avalanches, concentrated by elevation and much denser than direct accumulation (Hewitt, 2011).

Hasanabad is the major exception, the only south-oriented basin in these clusters of glaciers known to have formed ice dams. However, both of its tributary basins descend from rock walls of exceptional height and steepness. In addition, Hasanabad benefits from large avalanche deposits and steep ice falls descending from the Batura peaks. To their junction, Muchuhar descends from 7,794 m (Batura IV), a total of 5225 m in 22 km. Shispare descends from 7,611 m (Shispar Peak), or 5044 m in 16 km. The whole descent of 5774 m in the 1890s represents the largest and steepest of any glacier with a history of ice dams and GLOFs.

The clusters of termini and dam sites are in longitudinal river valleys that follow the primary geological structures of the orogen. Although deeply entrenched, the streams have relatively gentle thalwegs and extensive valley fill sediments. Valley floors are arid but river catchments extend into or are fed by heavily glacierized basins. These have the potential to support large lakes in the ablation season. All glaciers in the five clusters are

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established as surge-type except one, Batura First. It does show a variety of movement fluctuations indicative of recurrent instabilities (Batura Investigations Group, 1979). These sites and glaciers warrant special attention, and we present most of our specific results for them.

Figure 6 around here

3.4.1. Shaksgam Valley

The upper Shaksgam River, a tributary of the Yarkand on the north flank of the Karakoram, has the greatest number of reported GLOF events in recent decades. First reports has been from explorers (Anonymous, 1930; Barrow, 1888; Brunsden and Jones, 1984; Collie, 1902; Conway, 1897; Desio, 1930; Feng, 1991; Godwin-Austen, 1864; Hedin, 1917; Iturrizaga, 2005b, 2005c; Longstaff, 1950; Mason, 1929, 1928; McCormick, 1895; Neve, 1913, 1911; Visser, 1926; Visser and Visser-Hooft, 1938; Wenying et al., 1984; Younghusband, 1904). Scientific investigations began in the mid-1980s, including some monitoring of Kyagar (Keyajir) and Singhi (Telamukanli) glaciers (Zhang, 1992). These glaciers have the most remote, least visited dam sites. However, flood waves maintain identifiable GLOF characteristics and can be measured at a gauging station (Kaqun) some 500 km downstream (Hewitt & Liu, 2010). Five glaciers have clear geomorphic and depositional legacies of past ice dams, but known cases are almost all assigned to Kyagar Glacier, responsible for major GLOFs in recent decades (Fig. S5). The Kyagar ice dam has been studied recently using temporal DEMs, and automatic time-lapse photography for surface displacement (Haemmig et al., 2014; Round et al., 2017).

Between 2009 and 2017, five Kyagar lakes have been identified on satellite imagery, two followed by large GLOFs (some examples presented in Fig. 2). The floods occurred during the summer period. A GLOF on November 5th, 1998 is the only known winter event (Hewitt 2014).The glacier last surged in 2014-2016 (Fig.3). Surface

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displacement of Kyagar Glacier during the recent surge (2014-2015) is at least two times higher than the previous event (1994-1997) (Fig. 3 and 4). However, uncertainty arises because only satellite images at two years' interval were available for the earlier event, compared to one- year for the latest surge.

Surface elevation changes show that from 2000 to 2012 Kyagar lost mass in the receiving zone (358×10^6 m^3 $\pm$ 199×10^6 m^3), but mass increased in the reservoir zone (2259×10^6 m^3 $\pm$ 1173×10^6 m^3) (Fig. S6). The active surge began with the onset of the 2014 melt season (May) and continued for 15 months (August 2015). It has been suggested that the surge mechanism here is hydrologically controlled (Round et al., 2017). Subsequently, a comparison of three ASTER DEMs (August 2014; May 2017 and December 2017) with the SRTM again indicated mass gain in the receiving zone (Fig. S6). The Kyagar surge was also marked by two annual cycles with the peak surge velocities in the summer 2014-2015 suggesting similarities to Variegated Glacier in Alaska (Kamb & Engelhardt, 1987).

A sudden deceleration in surface movement was reported to coincide with the release of the GLOF from Kyagar Glacier ice dam on 27 July 2015 (Round et al., 2017). The GLOF may have been released through the hydraulic opening and/or melting of sub-glacial channels. Two more floods occurred on 17 July and 11 August 2016 (Round et al., 2017).

Based on high-resolution Planet team images (Planet Team, 2017) we observed another, smaller flood between 11-08-2017 and 19-08-2017 (Fig. 2). Surface displacement data suggest that from 27-07-2017 to 19-08-2017, average surface movement near the ice dam was about 1.5 m/day. Images also show the later flood drained along the ice margin rather than sub-glacially (Fig. 2). In addition, calving of ice from the glacier allowed the lake to expand towards the retreating ice wall.

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We observed maximum surface displacements for Staghar Glacier of up to 13 m d^{-1} during the winter of 1989. It is the third highest measured movement. The only other glacier with a confirmed ice dam in recent decades for this cluster was at Shinghi (Telamukanli) Glacier in the mid-1980s (Zhang, 1992). Field observations (1985, 1987) suggest that the Shinghi lake emptied rapidly through expanding subglacial channels (Zhang, 1992). For Shinghi Glacier, in all images studied during the 1990-2017 period, an average maximum surface displacement of ~160 m/y^{-1} was observed (Fig. 3). There were two periods of accelerated surface displacement during 1991-1998 and 2005-2011 and abrupt peaks (two-fold increase) in the 1993-1994 period and 2008. Along with surface features, (e.g. ice pinnacles, crevasses, shear margin and deformed medial moraine), the observations indicate it is surge-type, but the degree of movement heterogeneity poses a singular challenge for predictive purposes.

3.4.2. Upper Shyok valley

The second largest concentration of known ice dams is on the upper Shyok River, eastern Karakoram, with at least 20 events reported to date (Table S2). Major dams and GLOFs are identified with more than ten events for the Kichik and Chong Kumdan glaciers, some for the Aktash (1848, 1850) and Sultan Chhusku (1835). Most GLOFs on record occurred in the 19th and early 20th centuries (Hewitt 1982). Local residents told early explorers of a long history of GLOFs, the oldest on record being for 1533 (Table S2). In this and most other early cases, it is not known which of the Kumdan glaciers was involved (Hewitt, 2014). Forecasting is complicated by the way these glaciers and others have, on some occasions, advanced across the rivers without sealing a dam while some impoundments that did form drained slowly.

Kichik Kumdan Glacier blocked the flow of Shyok River in 1902-03, but not in the advances since, specifically not in 1935-1936; 1970-1972 and 1998-2000. The most

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destructive GLOFs recorded on the Indus came from Chong Kumdan Glacier between 1926 and 1933. The largest, in 1929, was the first with some detailed monitoring of an ice dam. Flows into what was called Gapshan Lake were observed, and growth of the impoundment (Fig. 1D). Maximum length of the lake was 18 km. Breaching and most of the outburst flood was along a sub-glacial channel (Grant & Mason, 1940). Arrival times and dimensions of the GLOF were monitored at sites down to Attock in the Indus plains (Hewitt, 2014). Regular warnings along the Shyok and Indus Rivers reduced loss of life (Gunn, 1930).

Since 2000, each Kumdan glacier has had independent, threatening surges, but without sealing large ice dams (Fig. S7). The Aktash Glacier advanced across the Shyok River between 2002 and 2009. Stream flow was maintained around or under the ice. In its most recent surge, Chong Kumdan Glacier had a maximum surge peak during May-June 2007 (Quincey et al., 2015). A large mass of ice (2039×10^6 m^3 $\pm$ 1088×10^6 m^3) was transferred from the reservoir zone to receiving zone during 2015-2000. The surge front rose ~160 m. However, fast flow terminated 4 km from the terminus, which then continued to advance more slowly into and across the Shyok. It did not seal a dam (Fig. 7).

Kichik Kumdan Glacier surged during 1998-2000. During the subsequent quiescent period (2000-2015), the surface of its lower receiving zone near the snout thinned by ~100m (Fig. 7). A surge of Aktash Glacier in 2007-2008 carried the terminal lobe across the Shyok River where, in 2010 the ice barrier reached a height of ~140 m. Again, the river continued to flow in a tunnel through the ice. There was no blockage (Fig. S7).

3.4.3. Shimshal valley

A third concentration of reported ice dams is in Shimshal valley, a tributary of the Hunza on the north flank of the main Karakoram. There is evidence of five glaciers damming the river (Table S2). Since 1882 some 11 major GLOFs are reported and another

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14 ice dams and minor GLOFs. The greatest number of GLOFs with the glacier identified has been from Khurdopin (ID 20) (Fig. S8). It blocks the ice-free lower Virjerab valley and is the largest surge-type glacier yet identified in the Karakoram (Fig. 1).

A GLOF in 1905 was attributed to the Malangutti Glacier (Table S2). Other cases are mentioned in local oral history and apparent in geomorphic features (Iturrizaga, 2006). Malangutti advanced across the Shimshal River in the early 2000s, but without forming a dam. Around terminus of Yazghil Glacier (ID 18) are also depositional remnants of former ice dams and it is mentioned as a source of floods by local residents (Fig. 1). Recently there have been abrupt changes in Yazghil surface displacement on four occasions in 1989-1990; 1996-1999; 2005-2006 and 2010-2011 (Fig. 2). The strongest peak flow was in 1997-1998 (Bhambri et al., 2017). The four pulses suggest a cycle of recurring instability with a threshold of 5 to 8 years. However, an implied instability for 2014 had not occurred as of the end of 2016. The terminus came close to sealing a dam in 2000 and was observed advancing in 1990, 1998 and 2006. Surface elevation change in the 2006 ASTER and SRTM DEMs showed mass gain in the receiving zone and near the snout (Fig. S9).

Recently, impoundments and small GLOFs have been associated with surges of Khurdopin Glacier. In 1999-2000, a surge blocked the Virjerab valley but the lake remained small and drained down the left side with minor local flooding (Hewitt, 2006, 2014) (Fig. S8). Local observers report a growing lake and small floods following a surge in 2017 (Steiner et al., 2018). Khurdopin Glacier showed surge peaks in its 1999 and 2017 advances. Quincey and Luckman (2014) reported ~20 years repeated surge cycle for this glacier based on 1978-79 and 1999 surge peak. However, the most recent surge of 2017 occurred after ~18 years (Steiner et al., 2018).

The 1998-1999 surge of Khurdopin Glacier appears in surface elevation changes when comparing ASTER DEMs with SRTM (Fig. S9). Afterwards this glacier lost mass in

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the lower ablation or receiving zone, while mass increased in the reservoir zone until another active surge began in April 2017 (Steiner et al., 2018). Khurdopin Glacier surged at higher speed in April through mid June 2017. At the beginning of summer in May 2017 we observed maximum surface displacement (~15 m d^{-1}) in what appears to be the greatest measured velocity for a Karakoram glacier (Fig. 3 and 4). The Khurdopin formed an ice dam that obstructed the water flow of the Virjerab River and created a small pond (0.08 km^2). Towards the end of July the ice dam was disturbed by high surface displacement. The lake area decreased by 0.02 km^2 and drained totally between 01 August and 05 August 2017. Satellite images (2017-2018) of Sentinel 2 suggest drainage through subglacial channels. Another small lake formed in late October 2017 and grew slightly (0.17 km^2) by February 2018. This suggests the closing of subglacial channels, possibility of a larger lake area in summer 2018, and a clear need to monitor this glacier at regular intervals.

3.4.4. Central Hunza valley

The fourth cluster of historic ice dams and GLOFs is in the main Hunza gorge (Goudie et al., 1984; Hewitt, 2006). In the late LIA some large active surges occurred and major GLOFs. There have been several active surges in recent years but no GLOFs.

Bualtar Glacier had major but erratic advances between 1987 and 2010, involving two active surges and effects of large landslides onto ablation zone ice (Hewitt, 2009). In the early 21st century the ice advanced over 3 km to come within 0.5 km of the historic ice dam site on the Hispar River.

A century ago, five relatively localized GLOFs were associated with surge events of Hasanabad Glacier in 1894, 1899, 1902, 1903 and 1904. There have been active surges since then, but the ice did reach or dam the Hunza River. One report of the Hasanabad Glacier surge of 1893-5 estimated an advance of 9.7 km in less than three months (Hayden, 1907). Another report gave a total advance of 11.5 km between 1892 and 1903 (Mason,

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1930). The sources do contain some contradictory statements (Goudie et al., 1984). In this case, evidently, two independent surges of the Muchuhar and Shispare branches became combined in the lower tongue. At other times, Hasanabad surges originate in just one of these two branches (Fig. 5). They last joined in 1979-80 but no surge was reported. In 2017-2018 there was a major surge of the Shispare branch of Hasanabad continuing at the time of writing. As noted above, Hasanabad is the only south-oriented basin in the clusters of glaciers known to have formed ice dams.

3.4.5. Karambar valley

The fifth valley with a history of multiple ice dams and GLOFs is Karambar, a tributary of the Ishkoman-Gilgit system in the western Karakoram (Hewitt, 2001; Iturrizaga, 2005a). At least six large Karambar GLOFs have been reported since 1844 (Table S2). Up to nine glaciers appear to have blocked the rivers in the past although only five are established as responsible GLOFs. Karambar Glacier is the most frequent.

Active surges of Karambar Glacier led to damming of Karambar River in 1844, 1865, 1895 and 1905 (Bhambri et al., 2017; Hewitt, 2014). The last of these led to the largest GLOF on record for the Gilgit basin, causing major damages in Gilgit town. The surges of 1930 and 1993 reached the river but did not dam it. Recent glacier surface displacement from 2014 to 2017 shows the normal flow of Karambar Glacier. However, in the same period, ice thickening near the snout is shown in multiple ASTER and SRTM DEMs (Fig. 8). Past surge intervals suggest another active surge and dam threat are likely in the next few years.

Chhatteboi (ID 3), forms a perennial, cross-valley ice dam and a self-dumping lake that fills and drains several times annually. It has its own independent rhythm (Fig. 1L, M). Of late, GLOFs from this site are too small to cause damage, but much larger lakes formed here in the past (Hewitt, 2001)

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Local reports and geomorphic evidence suggests that Chillinji Glacier dammed the Karambar in the late 19th or early 20th centuries, resulting in at least one GLOF. Actual dates are not known. In the past three decades irregular changes in surface velocity, increasing 3-, to 4-fold. These seem due to, or complicated by, the winter 1990-91 massive rock slope failure onto the ice (Fig. S2). It descended over the upper ablation zone, and continues to blanket about four km^2 of the glacier surface. Its debris has been transported some 10 km down the valley (Deline et al., 2014). The terminal lobe increased in height by ~25 m and tongue advanced by 150m between 2000 and 2005 (Fig. S10). During 2014-2015 and 2015-2016, surface displacement abruptly increased about 5-fold in the lower ablation zone. Chillinji has advanced to enter and cross the Karambar River and poses a current (2018-19) ice-dam threat. It has maintained an advanced position across the river and an ice barrier some ~130 m in height (Fig. 8). Small ponds, but no large lake or GLOF have yet been formed in this cycle (Fig. S10).

4. Discussion

Our inventory suggests, for the past two centuries, an average of one ice dam-derived GLOF annually, one major disaster per ten years, but clustered in time and sub-basin sources. A special, continuing threat relates to how Karakoram conditions differ from most other ranges of High Asia, the so-called 'Karakoram Anomaly' (Hewitt, 2005). Through the last ~30 years, episodes of glacier thickening and advance have been documented across the region, some with a potential to form ice-dams (Hewitt & Liu, 2010). Unlike the rest of the Himalaya and global trends, some evidence suggests total ice cover has been maintained since the 1970s, and increased in the highest parts of the Mustagh Karakoram (Bolch et al., 2017; Brun et al., 2017; Gardelle et al., 2013; Zhou et al., 2017). These developments raise unresolved questions of what will happen as global warming intensifies. Exactly how it relates to global climate change and will influence glaciations remain to be established.

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The Mustagh Karakoram does combine the greatest extent of extreme elevations and great relief anywhere, the greatest glacier cover for mainland Eurasia, and most of the largest valley glaciers outside high latitudes. It is distinguished by all-year snowfall accumulation, with large and nearly equal inputs of high altitude snow in winter and summer (Wake 1989). The larger part of glacier basin areas comprises rock walls with exceptional steepness and vertical range, contributing to massive wind redistribution of snow and avalanche-nourished ice (Dobreva et al., 2017; Hewitt, 2011, 2014). Also, most of the glacier termini creating ice dams on the upper Indus are shown to descend much lower than anywhere else in the HKH.

Some of these conditions may lie behind the high concentration and major role of surge-type glaciers, but no glaciologist has yet established what the links are. Recent work proposes a role for the Karakoram-West Tibetan Vortex, a newly discovered atmospheric system affecting regional climate (Li et al., 2018). It is not yet clear how this might affect glacier behavior and dam risk on the ground.

Interpreting these data in terms of risk first demands a caveat: in the larger scheme of natural hazards and disaster risk, it may seem GLOFs have a limited presence, even among cryosphere hazards. Very few appear in well-established disaster inventories (EM-DAT, 2018; Emmer, 2018, 2012; Institute, 2017; International Monetary Fund, 2012). In the five major river basins of the Greater Himalayan region (HKH), one inventory identifies almost 26,000 glacial lakes that could pose GLOF risks (Maharjan et al., 2018). Yet, over the past fifty years, barely a handful of GLOFs are reported that caused major damage (Hewitt & Liu, 2010; Ives et al., 2010; Kattelmann, 2003; Richardson & Reynolds, 2000). Two or three events in Nepal and Bhutan have dominated the recent literature (Emmer, 2018; Harrison et al., 2018).When a comparative or all-hazards assessment is adopted for mountain lands,

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earthquake, rainstorm floods, droughts, volcanic eruptions and epidemic disease can seem much more serious.

This said, large GLOFs, like most major disasters, are rare events with recurrence intervals of decades or centuries in any given region. But when they do occur the impacts can be staggering (Vuichard & Zimmermann, 1987). There have been periods when they were more frequent than recently. At present, it is widely thought that GLOF risk is changing for the worse in response to climate change, notably in the Himalaya (Haritashya et al., 2018).

Some have argued for a causal link between earthquakes and glacier surges but the Karakoram region, we have not found any reference to an actual impact of a seismic event on glacier surges, and ice-dam formation or failure. No direct connection between them has been demonstrated in North America (Post, 1969). The possibility of weakening of an ice dam by earthquakes has been discussed but remains speculative (Tryggvason, 1960).

Another relevant discussion concerns the role of ice thermal conditions. Again this suffers from inadequate data for the Karakoram. Work is limited to near-surface temperatures in shallow boreholes and accumulation zone snow pits, and for a very few glaciers such as Batura, Baltoro and Biafo (Hewitt 2014). What is available suggests that these glaciers have a range of thermal regimes; 'cold' (sub-freezing), 'warm' (at pressure melting point) and polythermal -- even in the same glacier, and changing over short time spans. This may well reflects the great elevation range of the glaciers and differences between those of northerly and southerly orientation. Partly it may involve complexities of all-year snowfall in accumulation zones, rather than predominantly summer, monsoonal (as to the east), and predominantly winter (as to the west). Recently a polythermal structure of a Himalayan debris-covered glacier has been revealed by deep borehole thermometry (Miles et al. 2018). The obvious need for such work in the Karakoram is clear, to understand how

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thermal conditions influence glacier movement generally, and exceptional numbers of surge-types in particular.

The slow down, possibly reversal of Karakoram ice reduction from the 1970s, is identified with a resurgence of ice dam activity in the 21st century. Four glaciers have formed ice dams in the current decade; Kyagar (ID 26), Khurdopin (ID 20), Chillinji (ID 5) and Aktash (ID 29). Only the first two dams generated serious dangers (Fig 4 and 6, Fig S8). Advances of ten others created cross-valley barriers but failed to seal an ice dam (Hewitt & Liu, 2010). Other events and conditions described since the 1990s show the risk continues and might even grow for a time in the Karakoram. However, so many surge-type glaciers and the intervention of large landslides onto glaciers compound the difficulties of predicting glacier response in these extreme high mountains.

In addition, even some large events have been ignored by international media, and it is important to recognize singular differences between local experiences within the mountains. Field experience and reports in the Karakoram point to hundreds of locally destructive GLOFs, some ice-dam related, most moraine-dammed, but unreported or poorly addressed outside the valleys where they occur (Kreutzmann, 1994). True, the same can be said of even more frequent and destructive snow avalanches, rock falls, debris flows, flash floods and wild fires. Even more significant for GLOF preparedness are modern trends that place more people, wealth and infrastructure at risk (Hewitt, 2014). In all it would be irresponsible for administrations or scientists to ignore the risk, and not to include them in the package of preparedness and warning systems for cryosphere hazards.

5. Concluding remarks

The complex largely unpredictable conditions identified do not mean the Karakoram climate is not changing. Nor do recent trends preclude a future, perhaps

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catastrophic, depletion of Karakoram ice in response to further climate warming. It does mean that the Karakoram is one of the few remaining areas with recurring glacier advances and ice dam hazards. The key unresolved issues concern which, or what combination of conditions outlined, exert the greatest control in those changes, not least the recently observed increased ice mass and multiple advances. The consensus among scientists is that global warming will overtake and reverse such developments (Sakai and Fujita 2017; Azam et al., 2018). In the unlikely event that greenhouse gas emissions are substantially reduced, the ice-dam GLOF risk could become more severe.

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Author contributions: R.B. and K.H. designed the study and completed writing of the manuscript. K.H. mainly supplied field-based and archival data, addressed concepts of ice-dammed lakes, Karakoram environments involved, and past evidence of movement heterogeneity of glaciers. R.B., K.H. and P.K. generated the Ice dams and GLOF inventory. R.B., A.M., P.K., S.M., A.K.,A.V., S.T. analyzed velocity measurements from sequential satellite images. R.B., P.K., S.M., A.K, A.V., S.T. generated DEMs and performed their analysis. All authors contributed to data interpretation and exchanges on the writing of the manuscript.

Declarations of interest

None.

Data and materials availability: Satellite images such as Landsat, Sentinel, and ASTER were accessed through the USGS and NASA portals. We have provided most of data in the supplementary materials. Additional data presented in the main text and supplementary materials may be requested from the authors.

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Figures and Tables

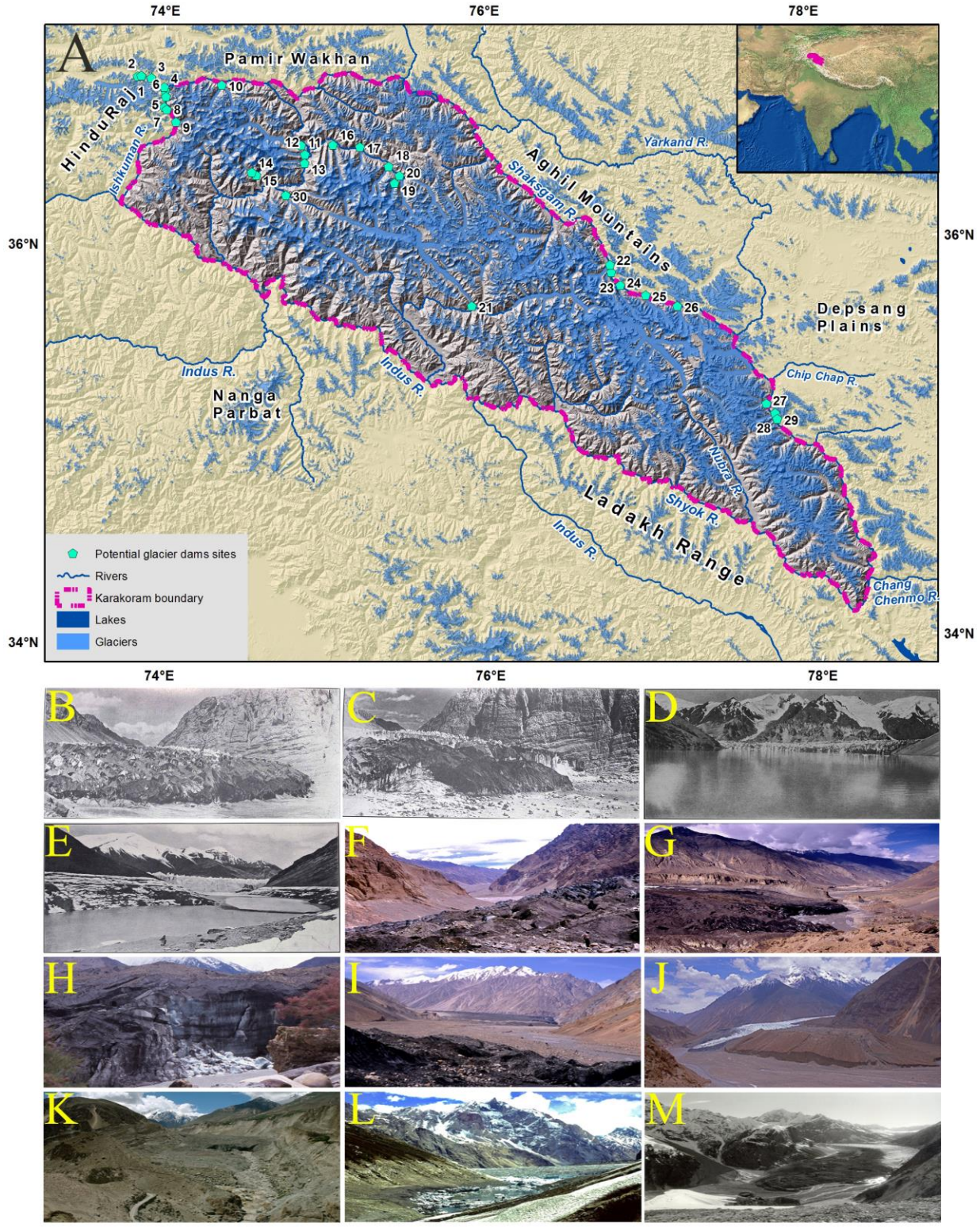

Fig. 1. Overview map of study area and ice dams. Landforms of past and potential glacier dam sites are illustrated based on previous field investigations (Table S1, 2). (**A**) Location of

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the Karakoram and neighbouring ranges that include the Hindu Raj, Pamir Wakhan, Aghil, Depsang and Ladakh mountains and NW Himalaya (Nanga Parbat). The hill-shaded background is presented by SRTM3 DEM. Glacier dams reported by previous studies are shown (Supplementary Table 1). Glaciers outlines are based on Bhambri et al. (2017) and RGI Consortium (2017). The Karakoram boundary is based on Royal Geographical Society and Survey of India nomenclature (Mason, 1938); (**B**) Terminus of Chong Kumdan Glacier (ID 27) from downstream before the ice dam broke (Photo J. P. Gunn 1929; (Gunn et al., 1930)). Chong Kumdan is the source of largest and most frequent source of GLOF on the Indus from ice-dams; (**C**) Terminus of Chong Kumdan (ID 27) Glacier from downstream after the ice dam broke (Photo J. P. Gunn 1929; (Gunn et al., 1930)); (**D**) The Chong Kumdan (ID 27) Ice dam from the lake on 12th August 1929 (Photo F. Ludlow; (Gunn et al., 1930)); (**E**) The Kyagar (ID 26) Glacier Ice dam across the Shaksgam Valley in 1926 (Mason, 1929); (**F**) Site of Khurdopin Glacier ice dam across the mouth of Virjerab valley in 2000. A small lake had recently drained. Trim lines of past lakes are visible on slopes above the river flats (Photo K. Hewitt 2000); (**G**) Malangutti Glacier advancing across the Shimshal River in 2000. It interfered with the river for about a decade but failed to seal a dam. Old moraines from past advances are visible on the opposing valley flank and, in the foreground, remnants of a massive rockslide responsible for a major, prehistoric, long-lived lake on the river (Photo 2000 K. Hewitt); (**H**) Malangutti ice advancing into the Shimshal River (Photo 2000 K. Hewitt); (**I**) East flank lobe of Yazghil Glacier advancing to the opposing valley wall, blocking the Shimshal River but not impounding a lake. View looking down the valley from outer moraines of Khurdopin and Yukshin Gardan Glaciers (Photo 2000 K. Hewitt); (**J**) West flank lobes of Yazghil Glacier. The fresh ice lobe is advancing into Shimshal River but would not seal a dam on this occasion. An old moraine-dammed, debris-covered lobe to the right side has been breached and abandoned in the contemporary

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advance (Photo 2000 K. Hewitt); (**K**) Bualtar Glacier advancing towards the junction with Hispar River in the right foreground, site of historic and prehistoric ice dams (Photo 2005 K. Hewitt); (**L**) Views of Chhatteboi-Karamabar ice dam site. Looking southeast and downstream from the small lake on the Karambar River. It had recently drained leaving icebergs stranded around the margins. Note the trim line of former much larger lakes dammed at this site (Photo 1993 K. Hewitt); and (**M**) Looking northwest and up-valley over the terminal lobe of Chhatteboi-Karamabar Glacier (Photo 1993 K. Hewitt). The ice dam is in the right middle distance. Sub figures (B-E) published with the permission of the Himalayan Journal.

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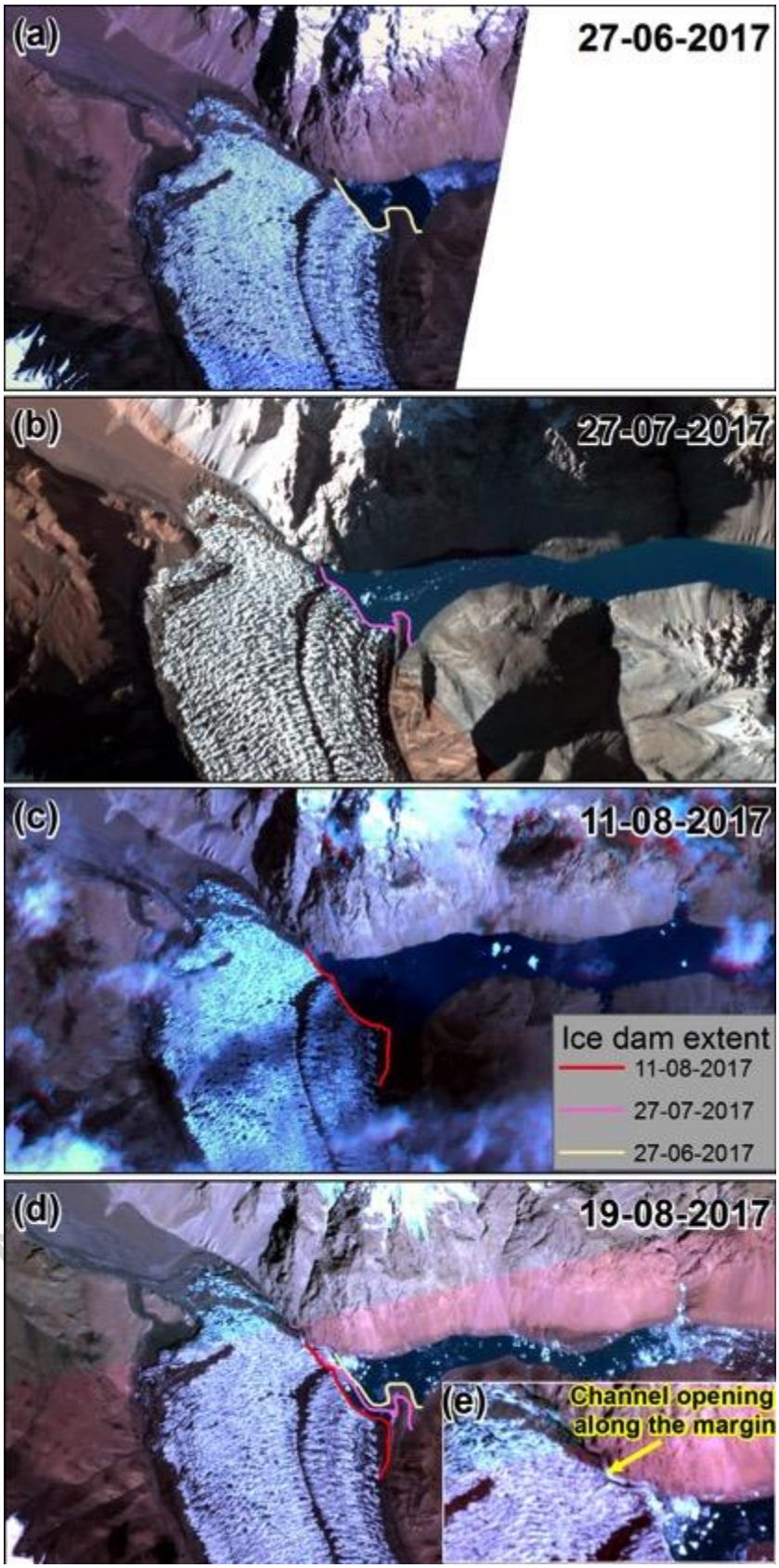

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Fig. 2. Overview of fluctuation in the lake extent formed by Ice dam of Kyagar Glacier during 2017. Background is presented by Planet images (a) 27-06-2017, (b) 27-07-2017, (c) 11-08-2017, (d) 19-08-2017 (Planet Team, 2017).The flood occurred between 11-08-2017 and 19-08-2017.

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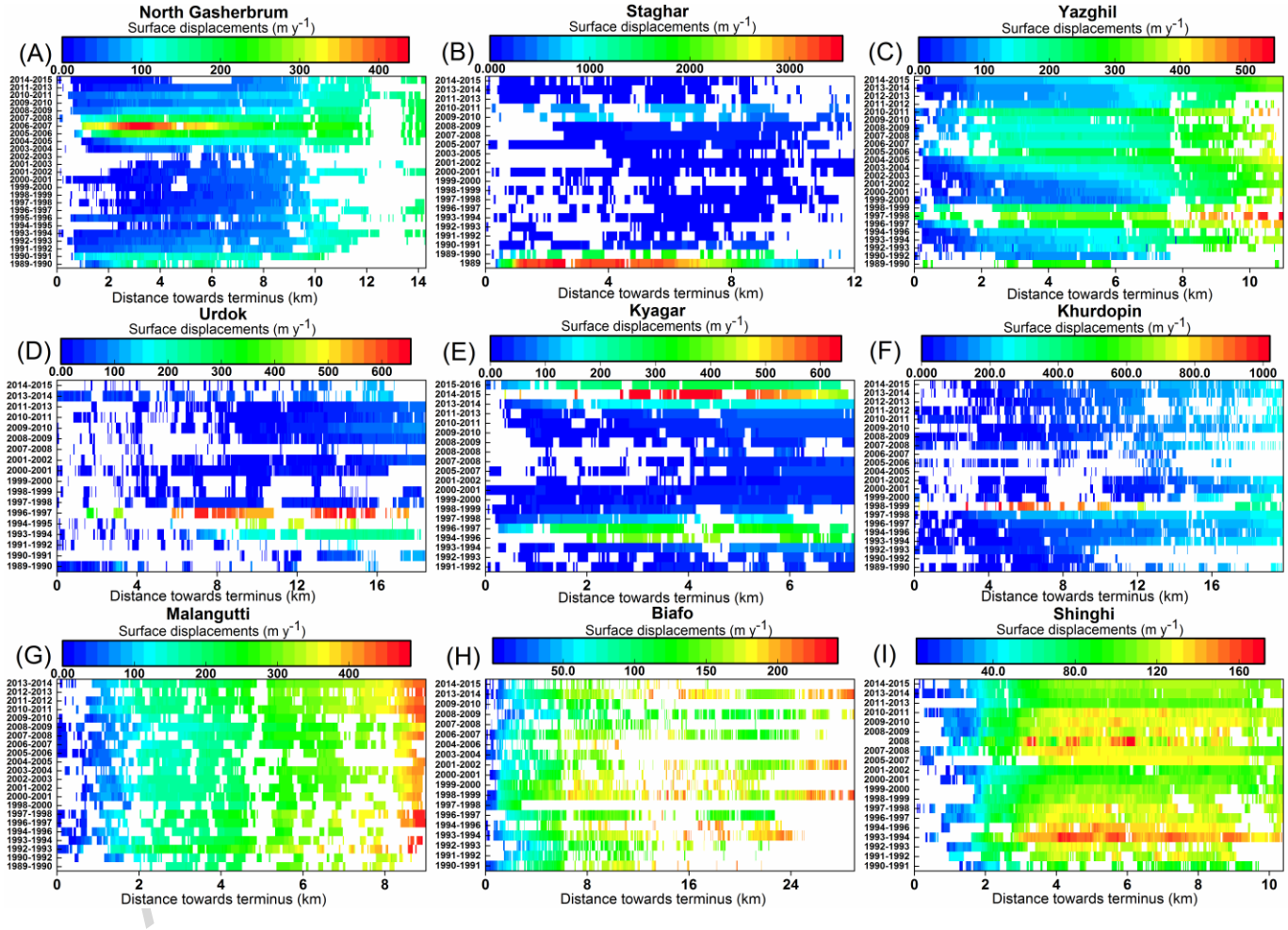

Fig. 3. Surface displacement of nine Karakoram glaciers from the 1990s to 2015-16. (**A**) North- Gasherbrum (ID 22), (**B**) Staghar (ID 24), (**C**) Yazghil (ID 18), (**D**) Urdok (ID 23), (**E**) Kyagar (ID 26), (**F**) Khurdopin (ID 20), (**G**) Malangutti (ID 17), (**H**) Biafo (ID 21) and (**I**) Shinghi (ID 25). Surface displacement generated using Image correlation software (CIAS) (Kääb & Vollmer, 2000). Satellite image pairs used for

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automated feature tracking including the estimated uncertainty presented in Supplementary Table 3. Location of surface displacement of these glaciers in the Karakoram is presented in Fig. 1 (glacier ID) and Table 1.

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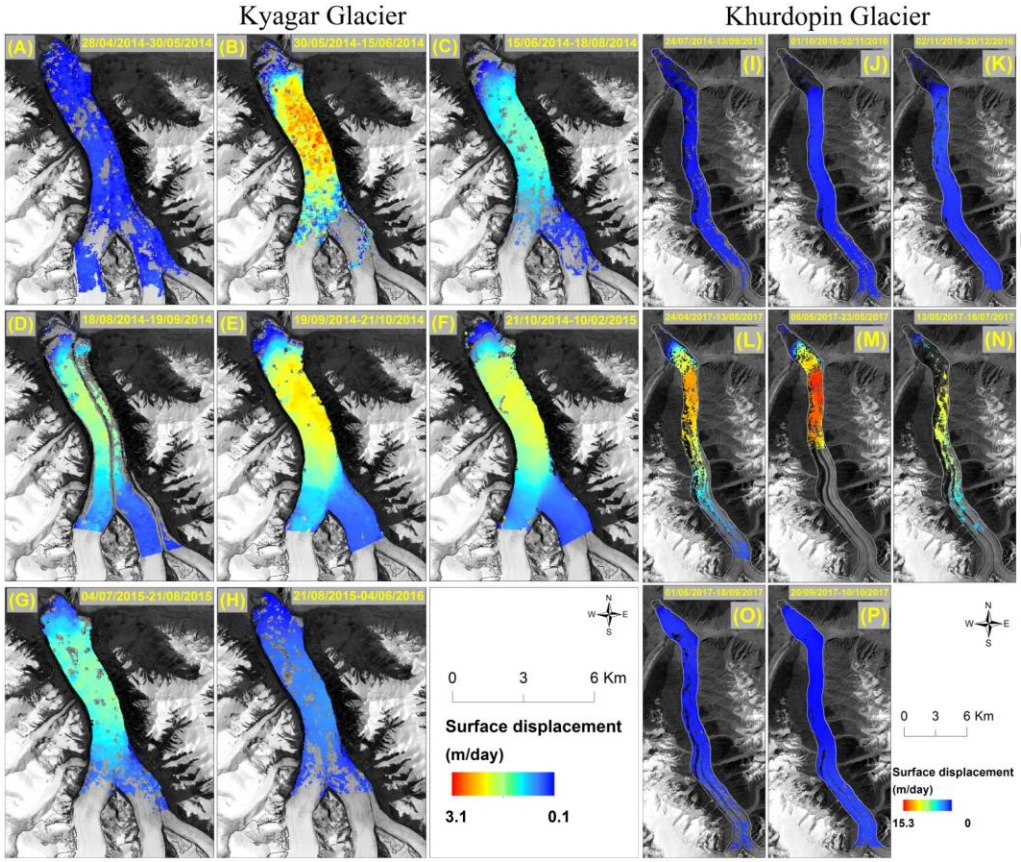

Fig.4. Surface displacement of glaciers. (A-H) Kyagar and (I-P) Khurdopin glaciers. Satellite image pairs used for automated feature tracking including the estimated uncertainty presented in Supplementary Table 3. Location of surface displacement of these glaciers in the Karakoram is presented in Fig. 1 (glacier ID) and Table 1.

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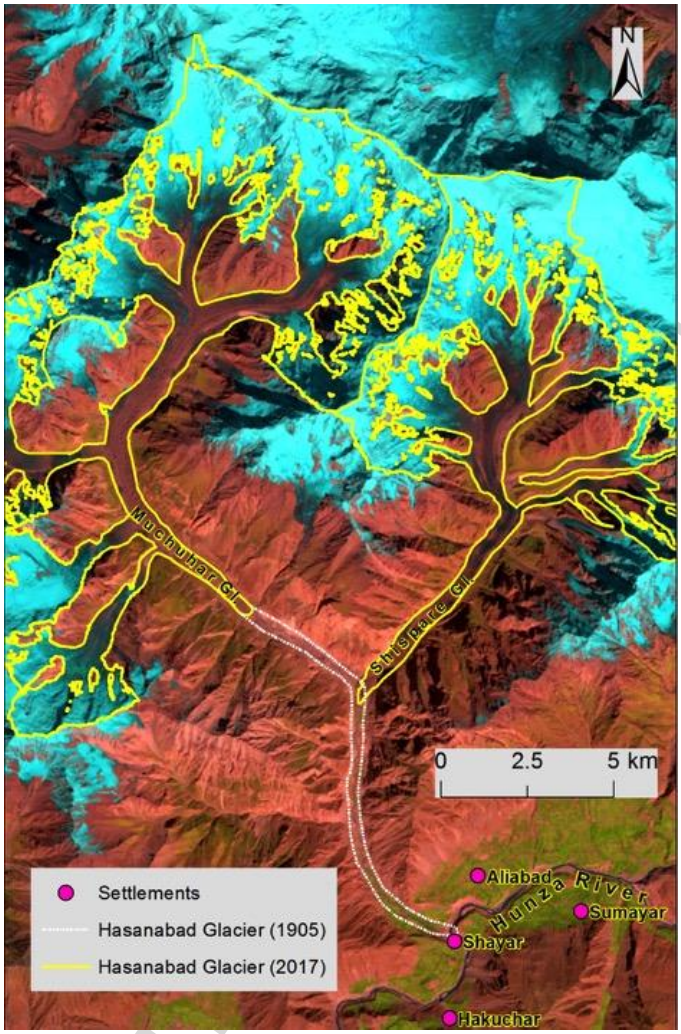

Fig. 5. Overview of the extent of Hasanabad Glacier in 1905 and 2017. It is to be noted that Hasanabad Glacier advanced 9.7 km within 2.5 months in 1904-1905 (Hayden, 1907). Further, this glacier detached into two tributaries Shispare and Muchuhar by 1954 due to 7 km retreat (Paffen et al., 1956). Again, both tributaries meet before 1972 due to the advance of Muchuhar (Bhambri et al., 2017). Shispare surged during 1972-76 and 1993-2002. However, Muchuhar could not meet with Shispare due to the retreat of ~4 km. Presently, Shispare and Muchuhar glaciers terminus is 8.1 and 12.3 km far from the Hunza River respectively. The background is presented by the Landsat OLI image (09-09-2017).

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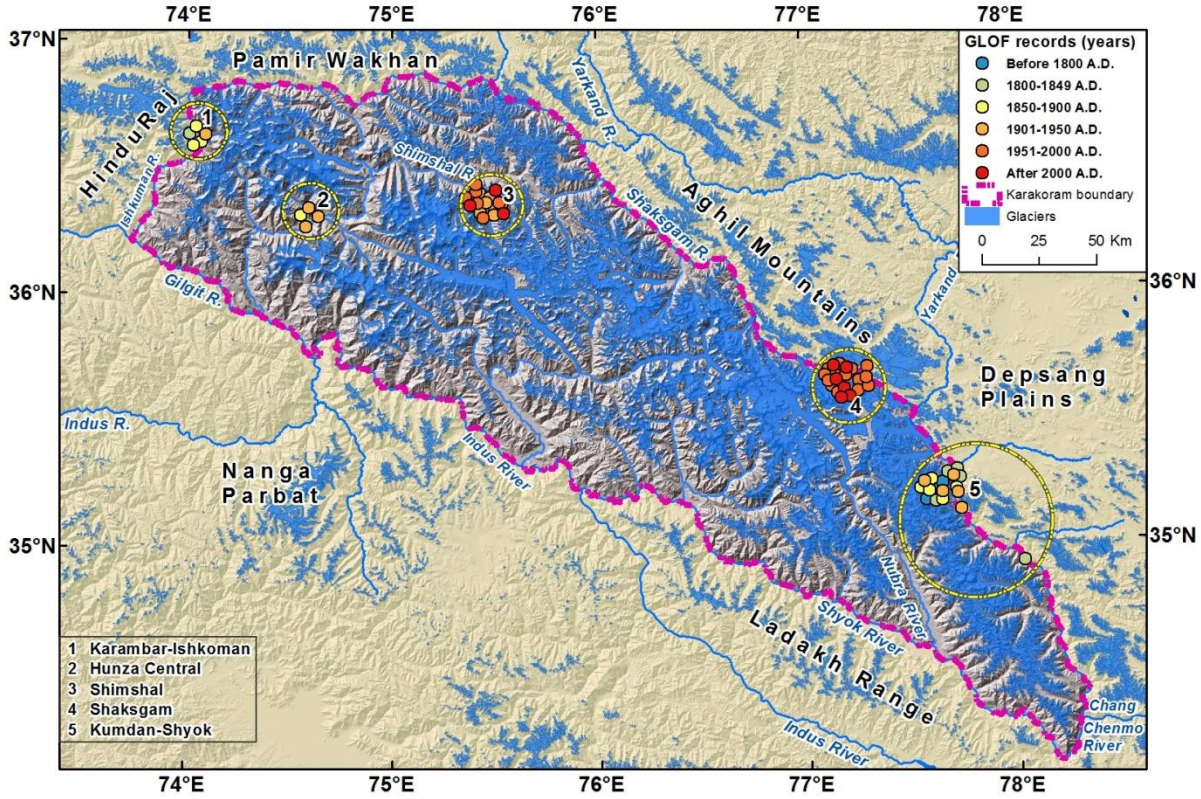

Fig. 6. Spatio-temporal distribution of GLOFs. Floods associated with five local clusters of Karakoram ice dams mainly from surge-type glaciers (see Table S2). From west to east, they are the 1) Karambar-Ishkoman, 2) Hunza Central, 3) Shimshal, 4) Shaksgam, and 5) Kumdan-Shyok clusters. During the last five decades, GLOFs are mainly limited to only two valleys i.e. Shimshal and Shaksgam.

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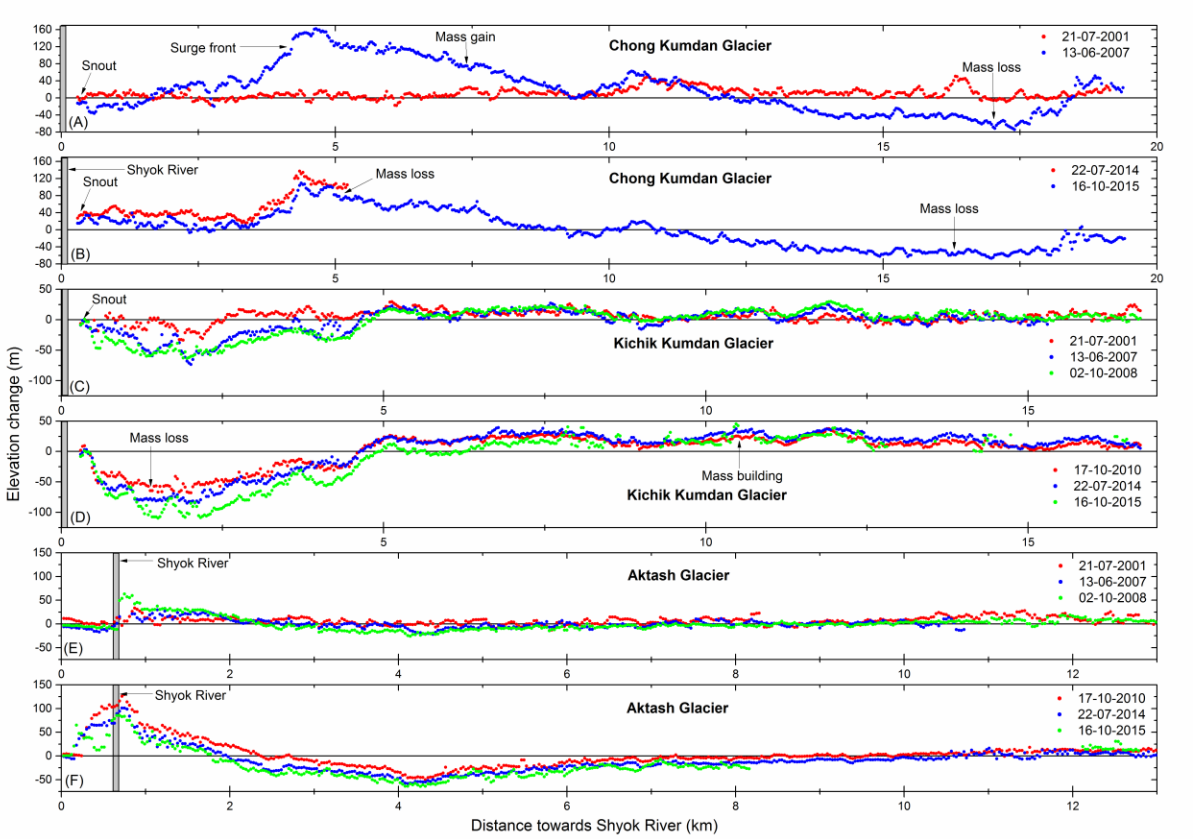

Fig.7. Elevation changes of glaciers associated with GLOF events. Elevation changes presented by Kumdan group of glaciers in the upper Shyok valley by Cartosat 1, ASTER and SRTM DEMs (Table S4). (A, B) Chong Kumdan; (C, D) Kichik Kumdan; and (E, F) Aktash glaciers.

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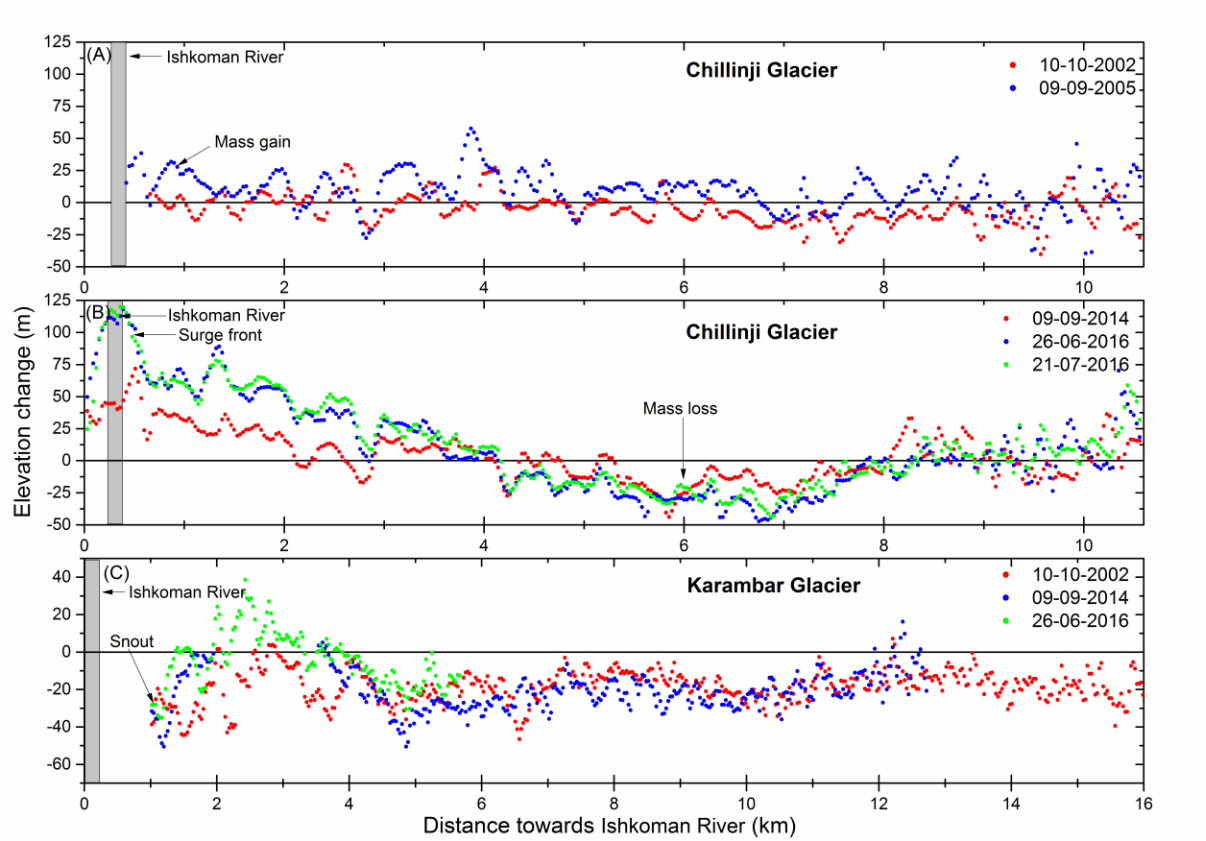

Fig. 8. Elevation changes of Chillinji Glacier (A-B); and Karambar Glacier (C) in the upper Ishkoman valley. Elevation changes are presented by ASTER and SRTM DEMs (Table S5).

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Table 1 Details of selected Karakoram glaciers with a history of ice dams and GLOFs. Surge classification, (Y) surge=type, (N) non-surge, (?) uncertain, (T) surge-type tributary. TIA, SD and EC represent temporal images analysis, surface displacement, elevation changes respectively.

ID	Name	Region	Surge-type	References	Satellite data analysis
1	Saklei Shuyinij	Karambar Valley	N	(Hewitt, 1982; Iturrizaga, 2005c)	TIA
2	Rochen Yaz		N	(Hewitt, 1982; Iturrizaga, 2005c)	TIA
3	Chhatteboi		N	(Hewitt, 1982; Iturrizaga, 2005c)	TIA and SD
4	Sotkher Rabot		N	(Iturrizaga, 2005c)	TIA
5	Chillinji		Y	(Hewitt, 1982; Iturrizaga, 2005c)	TIA, SD,and EC
6	Warghut		N	(Hewitt, 1982; Iturrizaga, 2005c)	TIA
7	Pekhin		N	(Iturrizaga, 2005c)	TIA
8	Saklei Buk		N	(Iturrizaga, 2005c)	TIA

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9	Karambar		Y	(Hewitt, 1982; Iturrizaga, 2005c)	TIA, SD, and EC
10	Yashkuk Yaz	Chapursan Valley	Y	(Hewitt & Liu, 2010)	TIA and SD
11	Batura First	Hunza Valley	Y? (T)	(Hewitt & Liu, 2010)	TIA and SD
12	Pasu		Y	(Goudie et al., 1984)	TIA and SD
13	Ghulkin		?	(Goudie et al., 1984; Richardson & Reynolds, 2000)	TIA and SD
14	Muchuhar		Y.	(Hewitt, 2014; Hewitt & Liu, 2010)	TIA
15	Hasanabad		Y	(Goudie et al., 1984; Hewitt, 2014; Hewitt & Liu, 2010)	TIA
16	Momhil	Shimshal Valley	Y	(Iturrizaga, 2005c)	TIA and SD
17	Malangutti		N	(Hewitt, 2014; Hewitt & Liu, 2010)	TIA and SD
18	Yazghil		Y	(Hewitt, 2014; Hewitt & Liu, 2010)	TIA, SD and EC

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19	YukshinGardan		Y (T)	(Iturrizaga, 2005b)	TIA, SD,and EC
20	Khurdopin		Y	(Hewitt, 2014; Hewitt & Liu, 2010)	TIA, SD,and EC
21	Biafo	Braldu Valley	N	(Hewitt, 2014; Hewitt & Liu, 2010)	TIA and SD
22	North Gasherbrum	Shaksgam Valley	Y	(Hewitt, 2014; Hewitt & Liu, 2010)	TIA and SD
23	Urdok		Y	(Hewitt, 2014; Hewitt & Liu, 2010)	TIA and SD
24	Staghar		Y	(Hewitt, 2014)	TIA and SD
25	Singhi		Y	(Hewitt, 2014)	TIA, SD,and EC
26	Kyagar		Y	(Hewitt, 2014; Hewitt & Liu, 2010)	TIA, SD,and EC
27	Chong Kumdan	U. Shyok Valley	Y	(Hewitt, 2014; Hewitt & Liu, 2010)	TIA and EC
28	KichikKumdan		Y	(Hewitt, 2014; Hewitt & Liu, 2010)	TIA and EC
29	Aktash		Y	(Hewitt, 2014; Hewitt & Liu, 2010)	TIA and EC
30	Bualtar	Hispar Valley	Y	(Hewitt, 2014; Hewitt & Liu,	TIA

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				2010)	

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Highlights

- Study updates inventory of ice dams and related GLOFs in the Karakoram combining historical sources and remote sensing data.
- Study reports recent evidence of surface displacement and elevation changes of surge-type and non-surge type glaciers involved in ice dam generation.
- Surge-type glaciers comprise or affect ~70% of inventory of ice dams and related GLOFs.
- Four glaciers formed new ice dams since 2008, two (Kyagar, Khurdopin) generating dangerous GLOFs.
- The glaciers of interest all exhibit recent advances, irregular movement, but with great variability and no clear relation to climatic fluctuations.

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